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Engineering Research into Traditional Timber Joints

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The most common form of joint in traditional oak-frame construction is the all-timber oak-pegged mortice and tenon joint. Although this is the stock-in-trade of the traditional carpenter, there has been little research work to investigate the joint's engineering behaviour. Why so little interest in this important topic? In Japan, where there are many historic timber buildings, there is a considerable body of research work investigating the engineering performance of buildings. Earthquakes do not respect the historic value of buildings and so it is important to have modern methods of assessment to preserve human safety. For example, the joints of Kiyomizu Dera in Kyoto have been the subject of much research work to determine their strength and performance under seismic loads (Chang et al 2009) (Figure 1).

Figure 1 *Kiyomizu Dera Temple Kyoto (left);*
Tests on traditional Japanese joints to determine seismic performance of Kiyomizu Dera joints (right)

In the UK we are fortunate not to have serious earthquakes and in most situations the design and fabrication of joints in traditional timber frames can be left to carpenters, who will size them by means of well-established principles of minimum size, spacing and proportion (Figure 2).

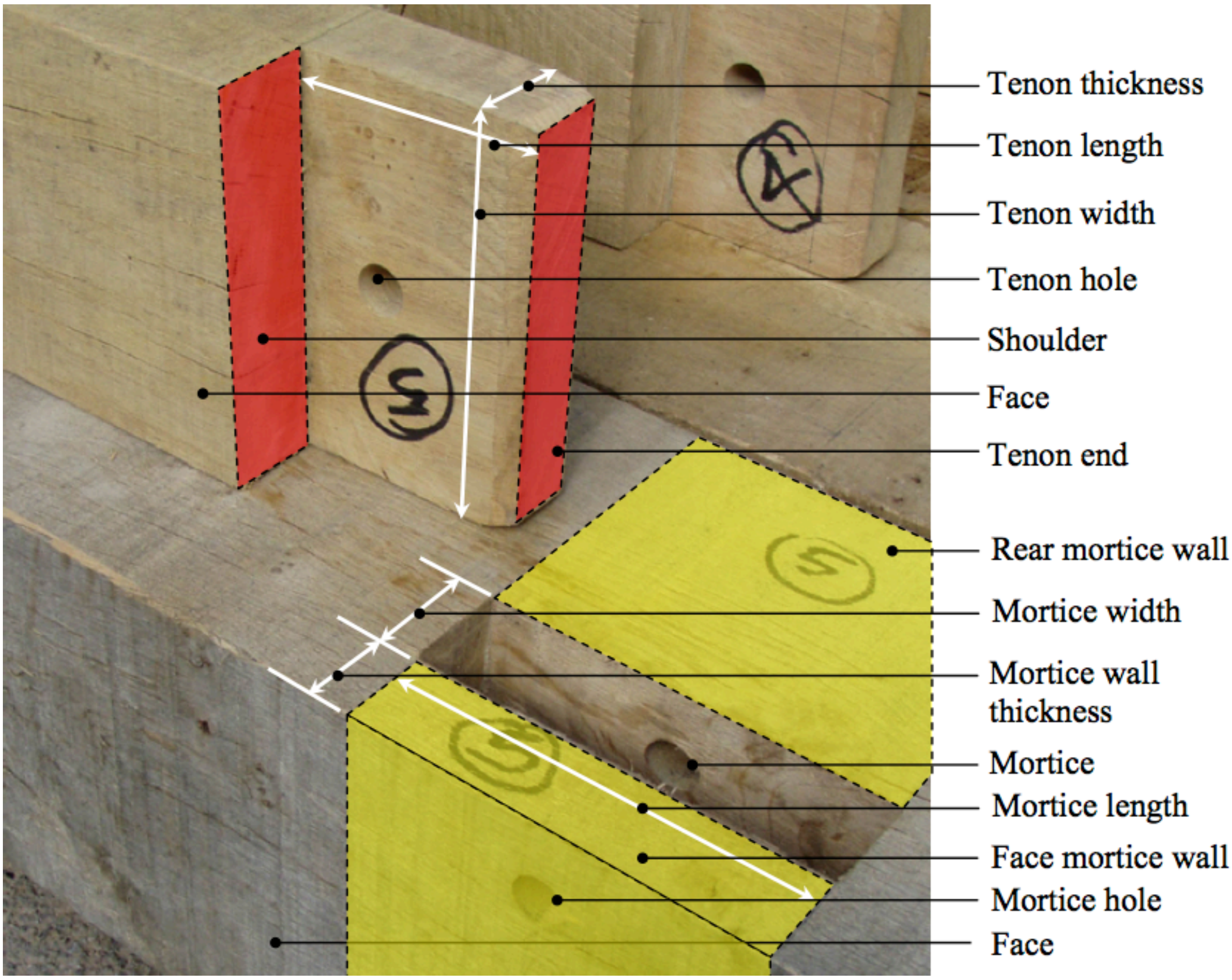

Figure 2 Traditional Mortice and Tenon joint - Terminology

However, there are situations where it is useful to know a traditional joint capacity. This may be in assessing a building for change of use to determine long-term safety, in making new extensions or repairs using a replication of historic detail, or in structures that draw upon historic techniques in contemporary building design. For whatever reason, it is clear that having an engineering assessment of mode of failure and mechanical performance can be very useful.

Prior to a study at the University of Bath, culminating with a PhD Thesis (Shanks and Walker 2005)), the majority of pegged all-timber connection research had been carried out in the US (Brungraber 1985, Mackay 1997, Bulleit 1999, Daniels 1999, Scholl 2000). The Shanks work developed a new understanding of the mode of failure of traditional mortice and tenon joints and provided information on the mechanical properties.

Being anisotropic, it is obvious that timber is a challenging material. Traditional joints have evolved over the centuries to efficiently resist loads. When working on traditional construction in timber, carpenters will often say the engineers make false, often conservative assumptions. Certainly it is common for engineers to assume that a mortice and tenon joint has little or no strength when pulled apart (often termed "pull out") and considerable strength and stiffness when closing. Carpenters who discover this simplifying assumption will point out that as joints shrink, the shoulder opens up (Figure 3)– inferring that the assumption of full transfer of compression load requires considerable movement. On the other hand, carpenters will point out that there there are no historic precedents of the carefully crafted pegged joints failing in tension. Thus, the simplifying assumption of full load transfer in compression and zero in tension is at odds with carpentry knowledge.

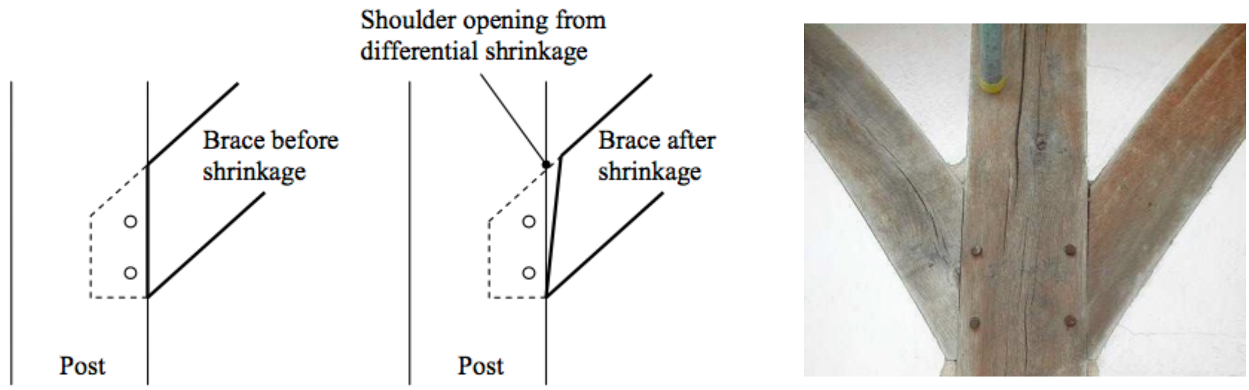

Figure 3. Joint before and after shrinkage (left); Typical brace-post joint in traditional frame (right)

Shanks' work has revealed a different mode of failure from that generally assumed. Modern joints in timber are by-and-large made with metal connectors (nails, screws and bolts). The engineering method of design for metal dowels assumes that the joint fails through a combination of bearing failure of the wood and plastic yield of the metal connector (Figure 4 (left). However, failure of the traditional timber pegged joints occurs almost solely in the oak peg.

Figure 4. Failure modes for dowelled joints in timber. Mild steel (left); Oak (right

On being loaded, oak pegged joints develop large shear deflection, which leads to the oak peg being trapped in the space between the faces of the wood, which, in a traditional joint, is the space between the mortice wall and the tenon (figure 4 (right)). The question the research posed was whether or not the same method of evaluating connector capacity could be modified for use in traditional joints. The model used for steel dowels is a good one and the research has revealed that, although an oak peg behaves in a very different way, a similar method can be applied to evaluate the strength of oak-pegged joints.

Design of structures should avoid sudden brittle failure. A key revelation of the research is that, because of the wedging effect of the peg, following initial failure there is a quasi-ductile pull-out as the tenon is withdrawn from the mortice.

The Green Oak Carpentry Company, Carpenter Oak and Woodland Company, and Oakwrights Ltd fabricated mortice and tenon test connections (Figure 5 (left)), comprising a 150 x100mm stud tenoned into a 200 x 200mm beam, The mortice was 150mm long, 40mm wide, 100mm deep and inset 38mm from the face of the beam (Fig 4). The tenon was 150mm wide, 38mm thick and 89mm long, also inset 38mm from one face of the stud. The connections were pegged with 19mm die driven dowels, tapered pegs, or turned pegs inserted through 19mm diameter holes. The tenon hole was offset from the line of the mortice holes by 3mm, towards the face of the beam, to induce a 'draw' which tightens the joint. The joint dimensions and draw follow common carpentry practices in the UK.

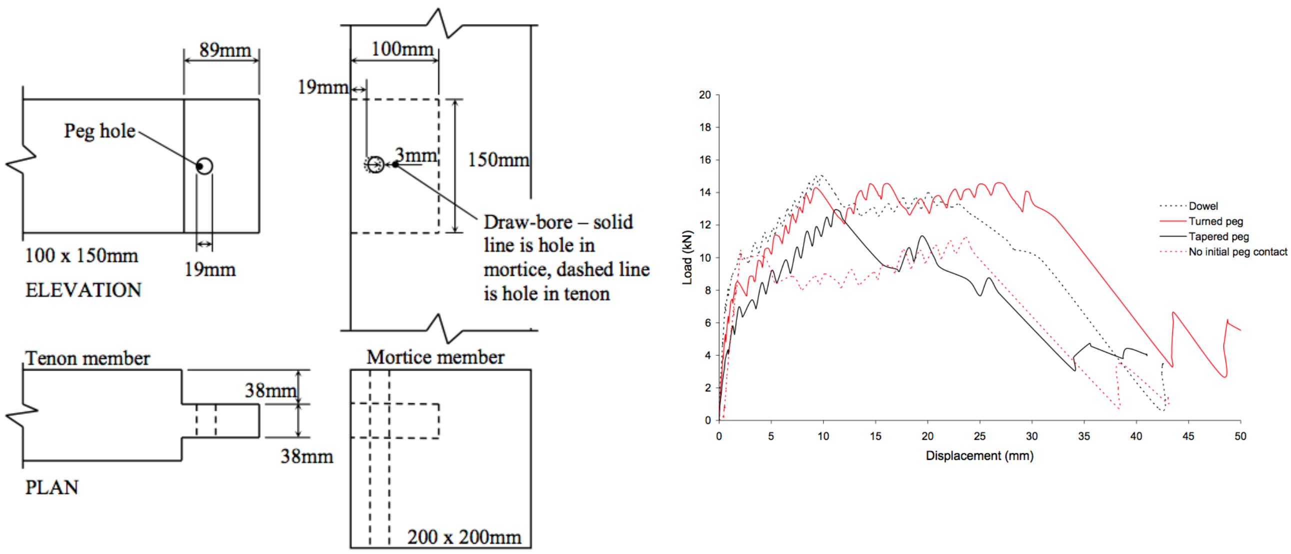

Figure 5 Typical joint geometry tested (left) and load-deflection plot (right)

Using well-established carpentry rules for the joints is very important. The tenon is restrained in the mortice, and adequate wall thickness for the mortice prevents the tenon splitting and the peg pulling out prematurely. If the peg is to pull-out through the tenon then a section of the tenon, or 'relish', must be sheared parallel to grain and correct end distance for the peg in the tenon prevents this. Figure 5 (right) shows a joint with correct detailing producing a stiff initial response followed by a long plateau of load as the wedged tenon pulls out.

The research led to a proposed design method for connection strength. This is based on a modified version of the method used for metal dowels. Whilst the shear deflection of an oak peg is very different from the plastic yielding of a metal dowel, the plateau of load before final failure gives prevents a sudden failure and enables a similar approach. The method used the expressions that form the basis for the methods adopted by the Eurocode and in very wide use for metal dowels (Johansen K 1949). A model for calculating connection stiffness was also developed (Shanks 2005).

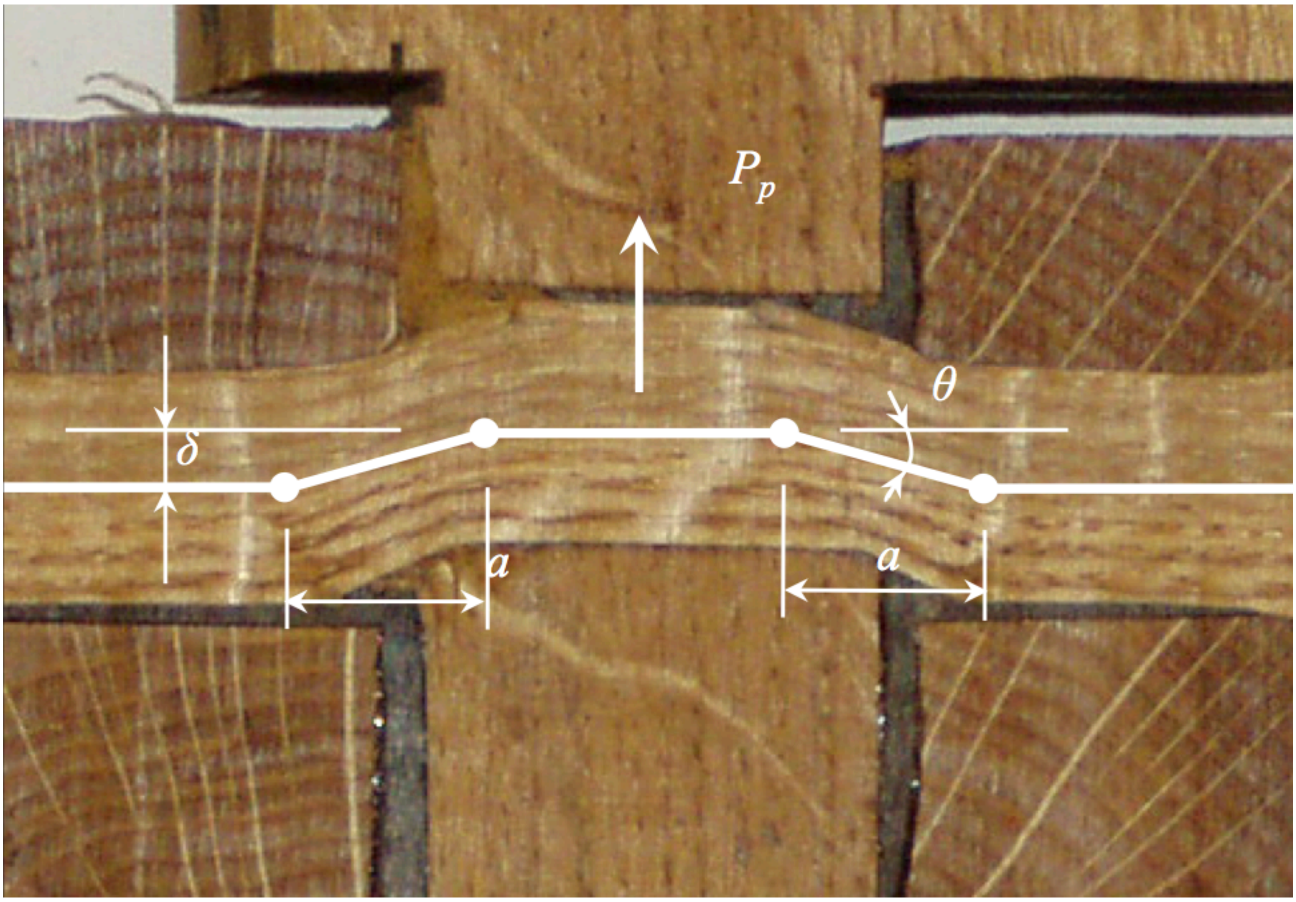

Figure 6. Four hinge failure of oak dowel in a traditional joint (Shanks 2005)

The tests showed an average ultimate strength of the pegged connections (figure 5) loaded in double shear was approximately 12kN (Shanks 2005). Significant deflection and energy absorption is observed with the pegged connections at the ultimate strength load, achieving the desired ductile failure mode.

The research project included tests on full size frames. The methods of evaluation of joint load and stiffness were used to predict the frame performance and the results were published (Shanks and Walker 2006). The method uses "embedment values", which are a measure of the bearing strength of the dowel on its hole. This was evaluated using bearing tests developed for the purpose.

The method leads to good predictions of load, although more validation work is needed if they are to be used on real structures.

The conclusions of the work, as set out in Shanks and Walker 2005, were summarised as:

• The three commonly used peg types in mortice and tenon connections (cleft tapered, cleft die driven and turned) have similar stiffness and strength characteristics in pull-out loading.
• Pull-out failure of a traditional pegged mortice and tenon connection is ductile.

• The effect of long-term loading and creep has not been investigated as part of this research. Joints were tested under very short term loading, but would be less stiff under much longer term loading.
• The EC5 method for calculating steel dowelled connections can be used to reasonably predict the failure load of timber dowelled connections.
• The peak load resisted by the connections in the pull-out tests is related to the dry density of the timber used to fabricate the dowels.
• Moment resistance of a pegged mortice and tenon connection can be related directly to the pull-out characteristics of the joint.
• Fit of the tenon within the mortice has an important influence on the load carrying capacity and action of the mortice and tenon in pull-out, bending and shear.

The research into traditional joints has continued internationally at the University of Kyoto (Shanks et al 2008), and University of Tasmania (Turbett 2013). Furthermore it has lead to a fertile theme of follow-up research at the University of Bath. The mode of failure applies to all fibrous dowels and the BRE Centre for Innovative Construction materials (BRE CICM) has continued the work in developing modern joints with GFRP dowels) *(*From Thomson et al 2010*).* These behave in a similar manner to oak dowels and enable a joint with strength and stiffness approaching steel but for lower cost and better fire and corrosion resistance. The work shows that traditional methods, developed over years of trial and error can inform and inspire in the development of modern methods.

However the main output of the work is in enabling structural engineers to make better predictions of the behaviour of traditional frames. The most common 'failure' for contemporary reinterpretations of traditional green oak framing is for the frames to fail to meet the serviceability limits for the structure. That is, the frames move under wind load, or creep over time beyond levels acceptable to the client. These deflection limits are often far more stringent than in historical structures because of modern building performance requirements such as sealing doors and windows. Proper understanding should allow engineers to make better assessment of the strength and stiffness of traditional frames, ensuring that traditional methods can be used for repair and ensuring that intervention is only made when absolutely necessary.

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